



Guidelines

Correlating CASS and Sand Erosion tests with outdoor environments



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1 Foreword

SolarPACES is one of several Technology Collaboration Programmes (TCP) organized in a framework of the International Energy Agency (IEA). It is an international cooperative network bringing together teams of national experts from around the world to focus on the development and marketing of concentrating solar power (CSP) and concentrating solar thermal (CST) systems.

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The guideline is open to amendments and updating as the state-of-the-art advances. Please send general comments, amendments or suggestions to florian.sutter@dlr.de and afernandez@psa.es.

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2 Symbols and abbreviations

| | |
|----------|--|
| AF | Acceleration Factor |
| A_{ic} | Sum of inner corroded area of reflector surface (= localized spot corrosion), excluding edge corrosion area. Corrosion spots touching the edges shall be considered as edge corrosion. |
| CASS | Copper Accelerated Salt Spray Test |
| CSP | Concentrating Solar Power |
| CST | Concentrating Solar Thermal |
| DSDD | Defect Size Density Distribution |
| χ | Threshold of the binary image to detect corroded area |
| SE | Sand Erosion Test |
| m_d | dust mass per unit area on the reflector surface in the sand erosion test [g/cm^2] |
| m_s | sand mass per unit area on the reflector surface in the sand erosion test [g/cm^2] |
| I_A | gray intensities per pixel of the aged image |
| I_R | gray intensities per pixel of the reference image |

3 Scope

Accelerated aging testing is a useful and necessary tool to evaluate the durability of CST reflectors. However, up to now, accelerated aging is usually used to compare different materials among each other (comparative testing) or for quality control purposes rather than to predict the performance in operational conditions.

This document provides correlations between two selected accelerated laboratory tests (Copper Accelerated Salt Spray Test, CASS, and Sand Erosion Test, SE) and outdoor environments for solar reflectors. Both laboratory tests have been described in detail in the IEC 62862-3-6 committee draft “Solar thermal electric plants – Part 3-6: durability of silvered-glass reflectors – laboratory test methods and assessment” [1].

The reflectors under the scope of this guideline are composed by a float-glass substrate and a reflecting silver layer on its backside, which is protected by a thin copper layer and an anticorrosive paint system composed by a primer and a top coating, and an optional intermediate coating. The herein discussed correlations are limited to silvered float-glass reflector types with the abovementioned layer stack, since differing coating types are likely to introduce unforeseen degradation modes, which might not be triggered under the CASS accelerated testing conditions.

Annex B of [1] already provides a brief description on how to approximately correlate the CASS and SE accelerated aging tests with outdoor exposure in different environments. The purpose of this guideline is to detail the methodology and measurement devices needed to develop the correlations, enabling the reader to develop such correlations by himself/herself for his/her environment or silvered-glass reflector type of interest.

4 Correlations

This section provides the erosion and corrosion correlations of the SE and CASS test with outdoor erosivity and corrosivity categories, respectively. The text of this section has slightly been adapted from the Annex B in [1].

4.1 Estimation of erosion in different outdoor environments

The SE test described in [1] aims at reproducing the erosion defects in size and density of the front-glass of samples exposed at a height of 1.5 m above ground not surrounded by a wind fence, collectors or any other barriers, in two types of desert environments (named as E1 and E2, in which E1 represents milder erosive conditions than E2). In general, a site where at least one of the following three conditions is fulfilled, should be regarded as an E2 site rather than an E1 site: (a) the soil exhibits a significant proportion of fine sand (in the diameter range of 60 to 200 μm), (b) the average relative humidity over a meteorological year lies below 30%, (c) events with wind velocities stronger than 10 m/s are taking place at least 300 hours per year. Further information on erosivity classification of the exposure site can be found in [3].

Procedure SE a) described in [1] can be used to simulate the expected near-normal specular reflectance loss after 5 years of exposure in an E1 environment, applying a dust mass m_d of 0.03 g/cm^2 (referred to the unit area of the reflector surface). Respectively, Procedure SE b) can be used to simulate 5 years of exposure in an E2 environment by using an m_d of 0.08 g/cm^2 and additionally a sand mass m_s of 0.37 g/cm^2 .

To simulate longer exposure durations, m_d and m_s shall be linearly scaled (e.g. simulation of 20 years in an E1 environment requires $m_d = 0.12 \text{ g}/\text{cm}^2$; simulation of 20 years in an E2 environment requires $m_d = 0.32 \text{ g}/\text{cm}^2$ and $m_s = 1.48 \text{ g}/\text{cm}^2$).

4.2 Estimation of corrosion in different outdoor environments

The ISO 9223 [4] specifies atmospheric corrosivity categories for metals and alloys (C1 - very low, C2 - low, C3 - medium, C4 - high, C5 - very high, CX – extreme) based on annual corrosion mass loss. According to [5], the CASS test described in [1] and [2] can be used for a rough estimation of the expected corrosion during outdoor exposure at sites of corrosivity categories C2, C3 and C4 (average corrosivity category of the reference metals copper, zinc, aluminum and steel).

For the study conducted in [5], the following approximation for the acceleration factor, AF, between CASS and environments with ISO 9223 corrosivity categories have been obtained for state-of-the-art silvered-glass mirrors:

AF= 400 for C2 environments,

AF= 300 for C3 environments,

AF= 200 for C4 environments.

NOTE For two samples of same coating types, one tested outdoors and one tested in CASS, the AF is defined as the ratio of exposure time in outdoor environment and the exposure time in CASS, producing an equivalent degradation pattern.

4.3 Estimation of overall degradation

Since degradation processes of glass erosion and silver-layer corrosion are independent from each other, the overall estimated reflectance loss of the sample can be expressed as the sum of reflectance losses caused by erosion (4.1) and corrosion (4.2). In certain outdoor exposure environments other degradation processes such as silver-tarnishing, solarization or non-removable soiling deposits can cause additional reflectance losses.

5 Measurement methods needed to develop the correlations

5.1 Method for automated erosion detection via image analysis

The method is based on the evaluation of images of the defects on the glass surface taken by microscope. The procedure is illustrated in Figure 1. The image acquisition process takes place using a 10-fold magnification objective (blue, top rectangle) and the so-called patchwork mode of the microscope software. Multiple adjacent images (in this case 7x7 for example) are taken and stitched together to compose a total area of around 0.5 cm². Thereby, a high magnification of a large area is achieved. A so-called flatfield image shall be taken at the same illumination and magnification conditions of the surface of a new reflector sample of the same type. By the application of a flatfield image subtraction, the uneven illumination pattern which is seen in Figure 1 can be removed. In the next steps an image analysis software shall perform the following steps: conversion to grey values, brightness thresholding and a binary conversion. The resulting objects are separated in size classes of 1 μm width, ranging from 1 μm to 50 μm and the quantity in each of the bins is given as density with respect to the evaluated reflector area. This leads to a defect size density distribution (DSDD), which is considered to be characteristic for erosion processes of particular environments. The magnification of the microscope shall be adapted to the observed defect size. As an example, Figure 1 shows the results obtained from a 50-fold magnification image as well (red bottom rectangle). In order to perform realistic erosion experiments under accelerated conditions in the laboratory, the DSDD of the outdoor exposed reflector materials shall be obtained by this method and afterwards be reproduced on new reflectors in accelerated aging chambers.

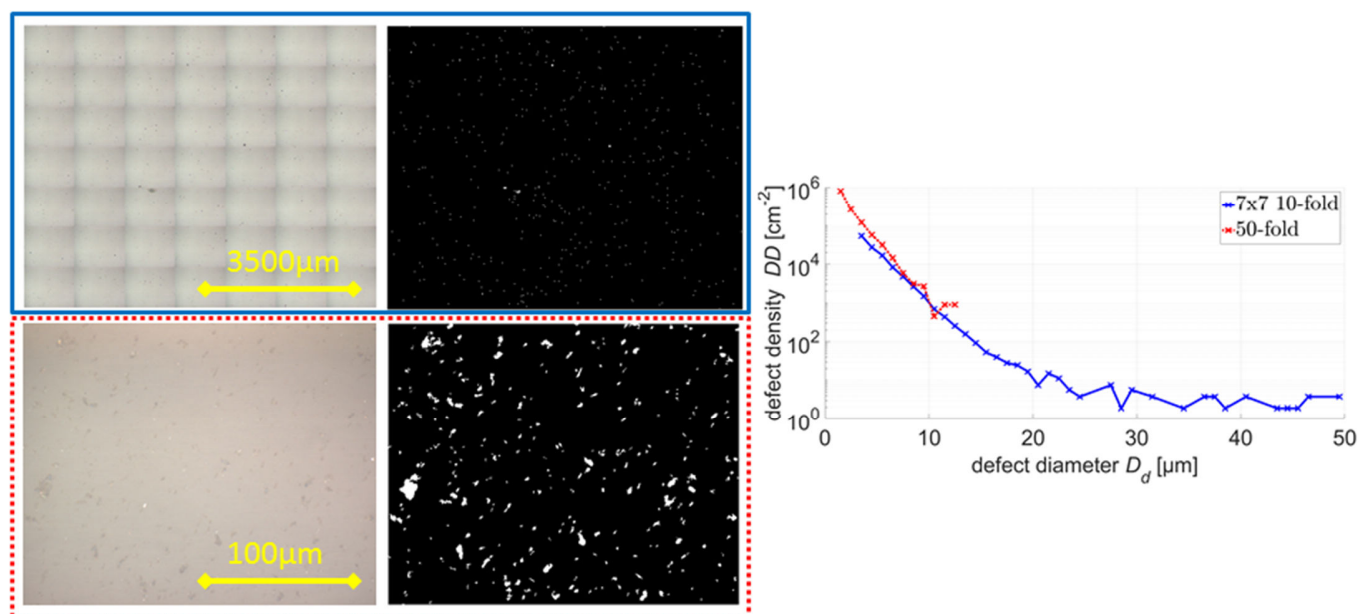


Figure 1: Illustration of the working principle of the defect detection on a 7x7 10-fold, and one 50-fold microscope image with their resulting DSDD.

5.2 Method for automated corrosion detection via image analysis

This method is applicable to measure the area of inner corrosion (localized spot corrosion), A_{ic} , of the samples. Edge corrosion shall be omitted in this method.

The inner corroded area shall be measured via a digital image analysis tool of resolution higher than 25 pixel/mm. It is recommended to use a digital monochrome camera with at least 8 bit pixel depth with low image noise, and to process unfiltered image raw data. It is recommended to mount the camera and the sample holder in a fixed position and inside a light-proof hermetic box (e.g. black painted box) to minimize the influence of positioning and external stray light. The angle between camera axis and normal vector of the sample should be kept as small as possible (perspective corrections are recommended). Although digital corrections shall be applied to compensate for light source aging or fluctuation, the light source illuminating the sample should be as stable as possible. Usage of a white light LED with LED driver of current accuracy of ± 10 mA is advised. The light source brightness and exposure time of the camera should be adjusted for the reference image to obtain an average RGB pixel intensity of around 30% below the maximum grey saturation value (as an example 255 for 8 bit pixel depth, and 16383 for 14 bit pixel depth), making sure that the maximum pixel range is not exceeded. Special care shall be taken to illuminate the sample homogeneously, so that pixel intensity variations are in the range $\pm 15\%$ across the surface of the reference image. Homogeneous illumination of the sample can be accomplished by illuminating it indirectly (e.g. by using a Lambertian screen or even a white paper).

The measurement procedure is as follows:

- Take an image of a non-aged sample (reference) of the same production batch as the aged reflector to be analyzed. The sample should be free of defects and any kind of dirtiness (*Reference image*).
- Place the aged mirror sample in the sample holder and make sure that the position and orientation are the same as for the reference image and take an image with identical illumination and camera settings (*Aged image*).
- Perform an RGB to grayscale conversion of the Reference and Aged images. Use the following equation (common practice formula for grayscale conversion):

$$\text{Grayscale} = 0.299 \cdot \text{Red} + 0.589 \cdot \text{Green} + 0.114 \cdot \text{Blue} \quad (1)$$

- Divide the resulting intensity of the *Aged image* by the intensity of the *Reference image* in each pixel to correct for light source inhomogeneities or dust on camera lens:

$$\chi = \frac{I_A}{I_R} \quad (2)$$

where I_A and I_R are the gray intensities per pixel of the *Aged* and the *Reference image*, respectively.

- Generate a binary image using a threshold of $\chi = 0.93$. A pixel is considered as black (=corroded) if $\chi < 0.93$. All other pixels are considered as white (=non-corroded).
- Crop the edges of the binary image to eliminate edge corrosion and shadowing effects caused by the perspective. If no edge corrosion is present, each image shall at least be cropped by 1.5 mm from the edges.
- Remove all the remaining black objects which are smaller than 5 pixels in extension. Two adjoining pixels are part of the same object if they are connected along the vertical, horizontal or diagonal direction (8- connectivity). Objects fulfilling this condition are regarded as noise.
- Remove all corrosion area touching the edges (including possible islands).

- Count the number of black pixels and divide by the sum of black and white pixels to obtain the inner corroded area A_{ic} .

Four exemplary setups to measure A_{ic} are reported in [6]. This publication also reports the expected uncertainty of the method, as determined by a Round Robin Test among the four setups.

6 Methodology followed to develop the correlations

7.1 Erosion correlation

The following three steps need to be undertaken in order to derive the acceleration factor between an outdoor environment and an accelerated laboratory erosion device:

1) Outdoor exposure of reflector samples on site

Several samples (at least 3 of each material) of the mirrors to be tested should be exposed on site at least for 3 years in order to identify the main degradation mechanisms, which affect the material (see Figure 2). Samples are installed into a rigid structure with south orientation in the north hemisphere and north orientation in the South hemisphere. The tilt angle should be similar to the latitude of the location where the samples will be placed and the height above ground should be between 1 and 2 meters. The samples should be periodically collected and analyzed in the laboratory. The parameters to be measured should be: monochromatic specular and spectral hemispherical reflectance, and most importantly defect size density distribution DSDD of the glass surface, which is the employed parameter to develop the correlation.

2) Reproduction of outdoor DSDD in laboratory setup

Specialized accelerated erosion setups shall be employed to reproduce the DSDD, which was measured on the outdoor exposed samples. A review of possible setups can be taken from [7]. As every installation is different, based on its operating principle and geometry, the various input parameters, such as wind speed or air pressure and the amount of sand used, will result in different erosion characteristics. Therefore, this guide does not give strict input parameters for custom built erosion setups. These must be chosen empirically by the operator to produce a similar DSDD on the samples to be eroded in the laboratory as on those obtained in the field. A reasonable way to start such an empirical study is to use wind speeds between 10 and 25 m/s and dust and sand masses outlined in section 4.1. As erosive materials the MIL-STD-810 blowing sand (particle diameter $< 150 \mu\text{m}$) and MIL-STD-810 blowing dust (particle diameter between $150 \mu\text{m}$ and $850 \mu\text{m}$) showed satisfying results and a mixture of both shall be used therefore. Both shall be composed mainly out of quartz (for further details see [8]). Respective erodent material can be purchased for example from KSL Staubtechnik GmbH (Lauringen, Germany).

The specific total amounts of m_s and m_d have to be modified while the other erosion parameters are kept constant until a satisfying overlap of resulting DSDD with the DSDD from the outdoor reflectors is accomplished. As an indication for a successful and realistic modeling, the respective reflectance values shall be compared as well, since they should be identical.

3) Determination of acceleration factor

Once it could be shown via image analysis, that a similar DSDD is established during the laboratory aging test and the outdoor exposed samples the acceleration factor AF is already determined. The amounts of m_s and m_d which have been used during the test to match the DSDD to the sample which was exposed outdoor for x months can be scaled linearly to simulate longer exposure durations.

For example, if the required amounts of sand and dust are 1 and 3 g/cm², respectively to provoke the same DSDD as measured on a reflector sample which was exposed for 3 years, sand and dust masses of 5 and 15 g/cm² shall be employed to simulate an exposure of 15 years. All the other erosion determining parameters have to be kept constant obviously. Further examples can be seen in [3].

7.2 Corrosion correlation

The following four steps need to be undertaken in order to derive the acceleration factor between the CASS test and a certain outdoor environment:

1) Outdoor exposure of reflector samples on site

Several samples (at least 3 of each material) of the mirrors to be tested should be exposed on site at least for 3 years in order to identify the main degradation mechanisms, which affect the material (see Figure 2). Samples are installed into a rigid structure with south orientation in the north hemisphere and north orientation in the South hemisphere. The tilt angle should be similar to the latitude of the location where the samples will be placed and the height above ground should be between 1 and 2 meters. The samples should be periodically collected and analyzed in the laboratory. The parameters to be measured should be: monochromatic specular and spectral hemispherical reflectance, and most importantly inner corroded area of the reflecting silver layer, A_{ic} , which is the employed parameter to develop the correlation.

2) Determination of corrosivity category of the site

The corrosivity category of the exposure site should be determined according to ISO 9223 [4]. For this purpose, metallic reference samples made of copper, zinc, aluminum and steel shall be exposed along with the reflector samples for at least one year and the mass loss of the reference materials shall be measured in order to categorize the site. The metallic reference samples are marked with a red oval in Figure 2.

This step is not mandatory since knowledge of the corrosivity category is not required in order to develop the correlation. However, it is useful to cross check the obtained acceleration factors with the ones reported in section 4.2.

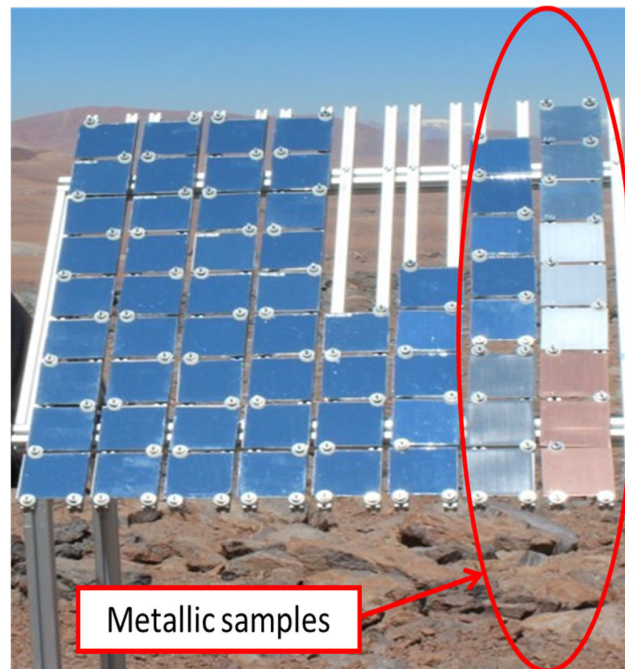


Figure 2: Exposure of reflector samples and metallic reference materials

3) Testing the reflector samples in CASS

The reflector samples of interest shall be tested in the CASS test (see [1] or [2]), preferably up to 2000 hours. Each 120 hours, the samples shall be taken out of the chamber to measure the inner corroded area A_{ic} with the method described in section 5.2.

As an example, Figure 3 shows the obtained data by DLR/CIEMAT for a certain type of state-of-the-art reflector.

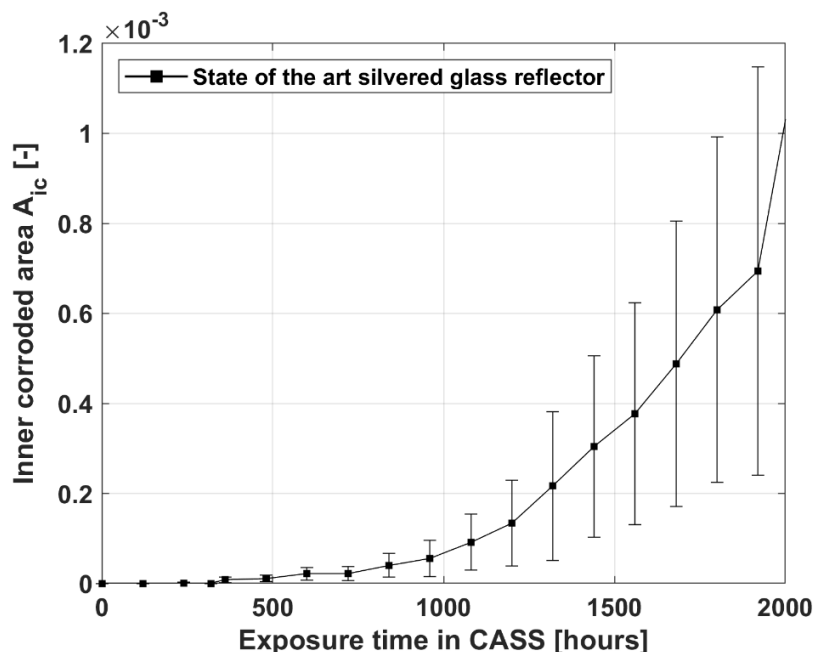


Figure 3: Evolution of A_{ic} during the CASS test for state-of-the-art silvered glass reflectors.

4) Determination of the acceleration factor

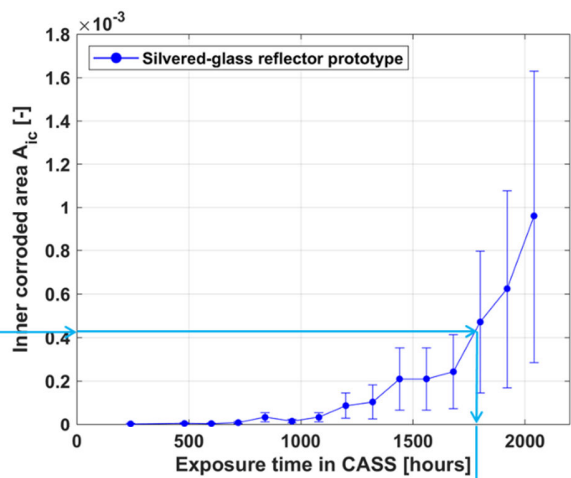
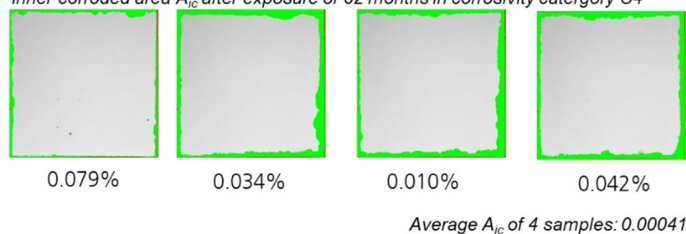
The acceleration factor is determined by comparing the A_{ic} of outdoor exposed samples in the environment of interest to the A_{ic} obtained during CASS testing.

Ideally, a similar exponential curve as shown in Figure 3 is recorded for the outdoor exposed specimens. It is recommended to represent both curves in the same graph with different time scales, one for CASS and another one for outdoor exposure. Both time scales should be chosen in such way that the exponential curves overlap as much as possible. The acceleration factor AF is then simply the factor between the two time scales.

Alternatively, punctual measurements can be used to compute the AF, as displayed in Figure 4. The AF is computed by dividing the outdoor exposure time by the CASS test chamber time if both samples, the outdoor and CASS tested one, show the same A_{ic} . The example of a prototype reflector in Figure 4 shows that the average of four outdoor exposed samples yields an A_{ic} of 0.00041 after 62 months. On the other hand, 1782 hours of CASS testing of the same sample type triggers the same A_{ic} of 0.00041. Thus, an AF of 25.5 is obtained.

The underlying assumption of the punctual measurement is that the corrosion propagation will follow the same exponential trend outdoors than in the CASS chamber. It is recommended to compute the AF for several different punctual outdoor exposure times to make sure that the results are consistent. For instance, for the example shown in Figure 4, the same analysis conducted after 36 months of outdoor exposure resulted in an AF of 27. Thus, for this material indeed the AF seems to be a material constant, strengthening the assumption above.

Inner corroded area A_{ic} after exposure of 62 months in corrosivity category C4



1782±149 h in CASS produce same corroded area than 62 months exposure at C4 site

$$AF = \frac{t_{outdoor}}{t_{CASS}}$$

AF_C4=25.5±0.1

Figure 4: Schematic on how to determine the acceleration factor between CASS and a C4 environment for a certain silvered-glass reflector prototype.

Once the acceleration factor is known, it the expected corrosion of the reflector in the outdoor environment can be estimated based on the CASS data. An acceleration factor AF_C4=25 means that 1 hour in the CASS chamber triggers the same corrosion as 25 hours in an outdoor environment of corrosivity category C4.

7 References

- [1] IEC 62862-3-6 committee draft “Solar thermal electric plants – Part 3-6: durability of silvered-glass reflectors – laboratory test methods and assessment”. To be published in April 2025
- [2] ISO 9227:2022 Corrosion tests in artificial atmospheres - Salt spray tests
- [3] Wiesinger, F.; Sutter, F.; Fernández-García, A.; Wette, F.; Wolfertstetter, F.; Hanrieder, N.; Schmücker, M.; Pitz-Paal, R.: Sandstorm erosion on solar reflectors: Highly realistic modelling of artificial aging tests based on advanced site assessment. *Applied Energy* 268 (2020) 114925.
- [4] ISO 9223:2012; 2012, Corrosion of metals and alloys – Corrosivity of atmospheres – Classification, determination and estimation, International Organization for Standardization, 2012.
- [5] Buendía-Martínez, F.; Sutter, F.; Wette, J.; Valenzuela, L.; Fernández-García, A.: Lifetime prediction model of reflector materials for concentrating solar thermal energies in corrosive environments. *Solar Energy Materials and Solar Cells* 224 (2021) 110996.
- [6] Wiesinger, F.; Baghouil, S.; Attout, A.; Le Baron, E.; Collignon, R.; Santos, F.; Diamantino, T.; Catarino, I.; Facão, J.; Ferreira, C.; Páscoa, S.; Sutter, F.; Fernández-García A.; Wette, J.: Detection of Corrosion on Silvered Glass Reflectors via Image Processing. *Results in Engineering* in 25 (2025) 103781.
- [7] F.W. Wiesinger, Erosion of solar reflectors in desert environments, Rheinisch-Westfälische Technische Hochschule Aachen, 2018.
- [8] MIL-STD-810G, Environmental Engineering Considerations and Laboratory Tests, Department of Defense, 2008, (n.d.).